DOCKET No.
HIT1P049/HSJ9-2003-0205US1

U.S. PATENT APPLICATION

FOR

SENSOR WITH IMPROVED STABILIZATION AND TRACK DEFINITION

INVENTOR(S):
Hardayal Singh Gill

ASSIGNEE: HITACHI GLOBAL STORAGE TECHNOLOGIES

SILICON VALLEY IP GROUP, PC
P.O. BOX 721120
SAN JOSE, CA 95172

SENSOR WITH IMPROVED STABILIZATION AND TRACK DEFINITION

FIELD OF THE INVENTION

The present invention relates to magnetic heads, and more particularly, this invention relates to read heads having magnetically pinned free layers in a free layer structure.

BACKGROUND OF THE INVENTION

The heart of a computer is a magnetic disk drive which includes a rotating magnetic disk, a slider that has read and write heads, a suspension arm above the rotating disk and an actuator arm that swings the suspension arm to place the read and write heads over selected circular tracks on the rotating disk. The suspension arm biases the slider into contact with the surface of the disk when the disk is not rotating but, when the disk rotates, air is swirled by the rotating disk adjacent an air bearing surface (ABS) of the slider causing the slider to ride on an air bearing a slight distance from the surface of the rotating disk. When the slider rides on the air bearing the write and read heads are employed for writing magnetic impressions to and reading magnetic signal fields from the rotating disk. The read and write heads are connected to processing circuitry that operates according to a computer program to implement the writing and reading functions.

In high capacity disk drives, magnetoresistive (MR) read sensors, commonly referred to as MR heads, are the prevailing read sensors because of their capability to read data from a surface of a disk at greater track and linear densities than thin film inductive heads. An MR sensor detects a magnetic field through the change in the resistance of its MR sensing layer (also referred to as an "MR element") as a function of the strength and direction of the magnetic flux being sensed by the MR layer.

The conventional MR sensor operates on the basis of the anisotropic magnetoresistive (AMR) effect in which an MR element resistance varies as the square of the cosine of the angle between the magnetization in the MR element and the direction of sense current flow through the MR element. Recorded data can be read from a magnetic medium because the external magnetic field from the recorded magnetic medium (the signal field) causes a change in the direction of magnetization of the MR element, which in turn causes a change in resistance of the MR element and a corresponding change in the sensed current or voltage.

Another type of MR sensor is the giant magnetoresistance (GMR) sensor manifesting the GMR effect. In GMR sensors, the resistance of the GMR sensor varies as a function of the spin-dependent transmission of the conduction electrons between ferromagnetic layers separated by a non-magnetic layer (spacer) and the accompanying spin-dependent scattering which takes place at the interface of the ferromagnetic and non-magnetic layers and within the ferromagnetic layers.

GMR sensors using only two layers of ferromagnetic material (e.g., Ni-Fe) separated by a layer of non-magnetic material (e.g., copper) are generally referred to as spin valve (SV) sensors. In an SV sensor, one of the ferromagnetic layers, referred to as

the pinned layer (reference layer), has its magnetization typically pinned by exchange coupling with an antiferromagnetic (e.g., NiO or Fe-Mn) layer. The pinning field generated by the antiferromagnetic layer should be greater than demagnetizing fields (about 200 Oe) at the operating temperature of the SV sensor (about 120° C) to ensure that the magnetization direction of the pinned layer remains fixed during the application of external fields (e.g., fields from bits recorded on the disk). The magnetization of the other ferromagnetic layer, referred to as the free layer, however, is not fixed and is free to rotate in response to the field from the recorded magnetic medium (the signal field). U.S. Pat. No. 5,206,590 granted to Dieny et al., incorporated herein by reference, discloses a SV sensor operating on the basis of the GMR effect.

An exemplary high performance read head employs a spin valve sensor for sensing the magnetic signal fields from the rotating magnetic disk. FIG. **1A** shows a prior art SV sensor **100** comprising a free layer (free ferromagnetic layer) **110** separated from a pinned layer (pinned ferromagnetic layer) **120** by a non-magnetic, electrically-conducting spacer layer **115**. The magnetization of the pinned layer **120** is fixed by an antiferromagnetic (AFM) layer **130**.

FIG. **1B** shows another prior art SV sensor **150** with a flux keepered configuration. The SV sensor **150** is substantially identical to the SV sensor **100** shown in FIG. **1A** except for the addition of a keeper layer **152** formed of ferromagnetic material separated from the free layer **110** by a non-magnetic spacer layer **154**. The keeper layer **152** provides a flux closure path for the magnetic field from the pinned layer **120** resulting in reduced magnetostatic interaction of the pinned layer **120** with the free layer

110. U.S. Pat. No. 5,508,867 granted to Cain et al., incorporated herein by reference, discloses a SV sensor having a flux keepered configuration.

Another type of SV sensor is an antiparallel (AP)-pinned SV sensor. In AP-Pinned SV sensors, the pinned layer is a laminated structure of two ferromagnetic layers separated by a non-magnetic coupling layer such that the magnetizations of the two ferromagnetic layers are strongly coupled together antiferromagnetically in an antiparallel orientation. The AP-Pinned SV sensor provides improved exchange coupling of the antiferromagnetic (AFM) layer to the laminated pinned layer structure than is achieved with the pinned layer structure of the SV sensor of FIG. **1A**. This improved exchange coupling increases the stability of the AP-Pinned SV sensor at high temperatures which allows the use of corrosion resistant antiferromagnetic materials such as NiO for the AFM layer.

Referring to FIG. **2A**, an AP-Pinned SV sensor **200** comprises a free layer **210** separated from a laminated AP-pinned layer structure **220** by a nonmagnetic, electrically-conducting spacer layer **215**. The magnetization of the laminated AP-pinned layer structure **220** is fixed by an AFM layer **230**. The laminated AP-pinned layer structure **220** comprises a first ferromagnetic layer **226** and a second ferromagnetic layer **222** separated by an antiparallel coupling layer (APC) **224** of nonmagnetic material. The two ferromagnetic layers **226, 222** (FM_1 and FM_2) in the laminated AP-pinned layer structure **220** have their magnetization directions oriented antiparallel, as indicated by the arrows **227, 223** (arrows pointing out of and into the plane of the paper respectively).

A key requirement for optimal operation of an SV sensor is that the pinned layer should be magnetically saturated perpendicular to the air bearing surface. Lack of

magnetic saturation in the pinned layer leads to reduced signal or dynamic range. Factors leading to a loss of saturation include demagnetizing fields at the edge of the pinned layer, magnetic fields from recorded data and from longitudinal biasing regions, current induced fields and the coupling field to the free layer.

Analysis of the magnetic state of pinned layers in small sensors (a few microns or less in width), reveals that due primarily to the presence of large demagnetizing fields at the sensor edges the magnetization is not uniform over the area of the pinned layer. FIG. **2B** shows a perspective view of an SV sensor **250**. The SV sensor **250** is formed of a sensor stripe **260** having a front edge **270** at the ABS and extending away from the ABS to a rear edge **272**. Due to the large demagnetizing fields at the front edge **270** and the rear edge **272** of the sensor stripe **260**, the desired perpendicular magnetization direction is achieved only at the center portion **280** of the pinned layer stripe, while the magnetization tends to be curled into a direction parallel to the ABS at the edges of the stripe. The extent of these curled regions is controlled by the magnetic stiffness of the pinned layer.

Furthermore, prior art AP-Pinned SV sensors use an AFM in order to pin the pinned layer magnetization. Most commonly used AFM materials have blocking temperatures (temperature at which the pinning field reaches zero Oe) near 200° C. This means that if the temperature of the SV sensor approaches this temperature, the pinned layer magnetization can change its orientation resulting in degraded SV sensor performance.

Although AP-Pinned SV sensors have large effective pinning fields because near cancellation of the magnetic moments of the two sub-layers results in a low net magnetic

moment for the pinned layer, thermal stability is still a concern because the operating temperatures of these SV sensors in disk files can exceed 120° C. In addition, the AP-pinned layer structure is vulnerable to demagnetization during processing operations such as lapping.

Therefore there is a need for an SV sensor that increases the magnetic saturation of the pinned layer and reduces the sensitivity to demagnetizing fields particularly at the front and rear edges of the pinned layer stripe. In SV sensors that include AFM layers to provide exchange anisotropy fields to fix the pinned layer magnetization direction, there is a further need for an SV structure that reduces the temperature limitations imposed by the blocking temperature characteristics of the commonly used antiferromagnetic materials required in prior art SV sensors for providing pinning fields.

In any of the prior art sensors described above, the thickness of the spacer layer is chosen so that shunting of the sense current and a magnetic coupling between the free and pinned layer structures are minimized. This thickness is typically less than the mean free path of electrons conducted through the sensor. With this arrangement, a portion of the conduction electrons are scattered at the interfaces of the spacer layer with the pinned and free layer structures. When the magnetic moments of the pinned and free layer structures are parallel with respect to one another scattering is minimal and when their magnetic moments are antiparallel scattering is maximized. Changes in scattering changes the resistance of the spin valve sensor as a function of cos Θ, where Θ is the angle between the magnetic moments of the pinned and free layer structures. The sensitivity of the sensor is quantified as magnetoresistive coefficient dr/R where dr is the change in the resistance of the sensor as the magnetic moment of the free layer structure

rotates from a position parallel with respect to the magnetic moment of the pinned layer structure to an antiparallel position with respect thereto and R is the resistance of the sensor when the magnetic moments are parallel.

The transfer curve of a spin valve sensor is defined by the aforementioned cos Θ where Θ is the angle between the directions of the magnetic moments of the free and pinned layers. In a spin valve sensor subjected to positive and negative magnetic signal fields from a moving magnetic disk, which are typically chosen to be equal in magnitude, it is desirable that positive and negative changes in the resistance of the spin valve read head above and below a bias point on the transfer curve of the sensor be equal so that the positive and negative readback signals are equal. When the direction of the magnetic moment of the free layer is substantially parallel to the ABS and the direction of the magnetic moment of the pinned layer is perpendicular to the ABS in a quiescent state (no signal from the magnetic disk) the positive and negative readback signals should be equal when sensing positive and negative fields from the magnetic disk.

Accordingly, the bias point should be located midway between the top and bottom of the transfer curve. When the bias point is located below the midway point the spin valve sensor is negatively biased and has positive asymmetry and when the bias point is above the midway point the spin valve sensor is positively biased and has negative asymmetry. When the readback signals are asymmetrical, signal output and dynamic range of the sensor are reduced. Readback asymmetry is defined as:

$$\frac{V_1 - V_2}{\max(V_1 \text{ or } V_2)}$$

For example, +10% readback asymmetry means that the positive readback signal V_1 is 10% greater than it should be to obtain readback symmetry. 10% readback asymmetry is acceptable in some applications. +10% readback asymmetry may not be acceptable in applications where the applied field magnetizes the free layer close to saturation. The designer strives to improve asymmetry of the readback signals as much as practical with the goal being symmetry.

The location of the transfer curve relative to the bias point is influenced by four major forces on the free layer of a spin valve sensor, namely a ferromagnetic coupling field H_{FC} between the pinned layer and the free layer, a net demagnetizing (demag) field H_D from the pinned layer, a sense current field H_I from all conductive layers of the spin valve except the free layer, a net image current field H_{IM} from the first and second shield layers.

Another factor that can affect readback asymmetry is positive magnetostriction of the free layer structure. If the free layer structure has positive magnetostriction and is subjected to compressive stress, there will be a stress-induced anisotropy that urges the magnetic moment of the free layer from the aforementioned position parallel to the ABS toward a position perpendicular to the ABS. The result is readback asymmetry. The compressive stress occurs after the magnetic head is lapped at the ABS to form the stripe height of the sensor of the read head. After lapping, the free layer is in compression and this, in combination with positive magnetostriction, causes the aforementioned readback asymmetry. It is interesting to note that if the free layer structure has negative magnetostriction in combination with compressive stress that the magnetic moment of the free layer is strengthened along the position parallel to the ABS. A high negative

magnetostriction, however, is not desirable because it makes the magnetic moment of the free layer structure stiff and less responsive to field signals from the rotating magnetic disk. Accordingly, it is desirable that the magnetostriction of the free layer be zero or only slightly negative.

Unfortunately, magnetostriction of the free layer is difficult to control in present sputtering deposition systems. A typical free layer structure includes first and second free layers wherein the first free layer is cobalt iron and the second free layer is nickel iron with the first free layer interfacing the copper spacer layer for increasing the magnetoresistive coefficient dr/R of the sensor. Typical compositions of the free layers are cobalt iron ($Co_{90}Fe_{10}$) for the first free layer and nickel iron ($Ni_{83}Fe_{17}$) for the second free layer. When these layers are formed by sputter deposition the free layer structure invariably has an undesirable positive magnetostriction. In the past, the positive magnetostriction of the free layers has been accomplished by changing the composition of the free layers, such as reducing the iron content in the nickel iron and/or reducing the iron content in the cobalt iron. Since there is typically more than one nickel iron and cobalt iron layer in the spin valve sensor, this means that the targets in the sensor have to be changed in order to change the composition and lower the magnetostriction of the free layer structure.

Another problem found with sensors is that when the sensor has a very narrow track width, AP layers become unstable. More particularly, the AP layers tend to become unpinned because the pinning strength becomes weaker as the width of the layers is decreased. What is needed is a way to stabilize pinned layers in a narrow track width sensor so that magnetic orientations of the pinned layers do not flip under electrical or

mechanical stress. What is also needed is a way to improve track definition by reducing magnetic interference caused by side reading.

SUMMARY OF THE INVENTION

The present invention overcomes the drawbacks and limitations described above by providing a magnetic head having an air bearing surface (ABS). The head includes a free layer structure having at least three layers. First and second free layers have magnetic moments that are pinned antiparallel each other. A third free layer, closer to the second free layer than the first free layer, has a magnetic moment oriented parallel to the magnetic moment of the second free layer. Ends of the third free layer define track edges of the third free layer. The first and second free layers extend beyond the track edges in a direction parallel to the ABS. The first and second free layers have near identical magnetic thicknesses and therefore the areas of the free layer outside the track edges (track edges defined by the edges of the third free layer) do not generate any signal and also provide magnetic stability to the free layer. The third free layer is exchange coupled with the second free layer, and is thereby stabilized by the second free layer.

Preferably, a net magnetic moment of the first and second free layers is negligible. Also preferably, the first and second free layers extend beyond the track edges for distances each at least as long as a length of the third free layer measured between its track edges. More preferably, the first and second free layers extend beyond the track edges for distances each at least five times as long as a length of the third free layer.

In one embodiment, a thickness of the first free layer is less than a combined thickness of the second and third free layers, the thicknesses being measured in a

direction perpendicular to a plane of the first free layer. Preferably, a thickness of the third free layer is greater than thicknesses of the first and second free layers individually, the thicknesses being measured in a direction perpendicular to a plane of the first free layer.

To further enhance the pinning of the portions of the first and second free layers, at least one antiferromagnetic (AFM) layer can be positioned outside the track edges of the third free layer in a direction parallel to the ABS, each AFM layer being for pinning a magnetic orientation of portions of the free layer closest thereto that are positioned outside the track edges of the third layer.

The head preferably further includes an antiparallel (AP) pinned layer structure that has at least two pinned layers having magnetic moments that are self-pinned antiparallel to each other. The AP pinned layer structure further stabilizes the free layer structure.

The head may also include a shield layer positioned above the free layer structure. To further reduce the effects of side reading from adjacent tracks, portions of the shield layer positioned outside the track edges can be made to extend downwardly towards the portions of the free layer structure positioned outside the track edges.

The head described herein may form part of a GMR head, a CPP GMR sensor, a CIP GMR sensor, a CPP tunnel valve sensor, etc. for use in a magnetic storage system.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and advantages of the present invention, as well as the preferred mode of use, reference should be made to the following detailed description read in conjunction with the accompanying drawings.

FIG. **1A** is an air bearing surface view, not to scale, of a prior art spin valve (SV) sensor.

FIG. **1B** is an air bearing surface view, not to scale, of a prior art keepered SV sensor.

FIG. **2A** is an air bearing surface view, not to scale, of a prior art AP-Pinned SV sensor.

FIG. **2B** is a perspective view, not to scale, of a prior art AP-Pinned SV sensor.

FIG. **3** is a simplified drawing of a magnetic recording disk drive system.

FIG. **4** is a partial view of the slider and a merged magnetic head.

FIG. **5** is a partial ABS view, not to scale, of the slider taken along plane **5-5** of FIG. **4** to show the read and write elements of the merged magnetic head.

FIG. **6** is an enlarged isometric illustration, not to scale, of the read head with a spin valve sensor.

FIG. **7** is an ABS illustration of a CPP GMR sensor, not to scale, according to an embodiment of the present invention.

FIG. **8** is an ABS illustration of a CPP GMR sensor, not to scale, according to another embodiment of the present invention.

FIG. **9** is an ABS illustration of a CPP GMR sensor, not to scale, according to an alternate embodiment of the present invention.

FIG. **10** is an ABS illustration of a CPP tunnel valve sensor, not to scale, according to an embodiment of the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

The following description is the best embodiment presently contemplated for carrying out the present invention. This description is made for the purpose of illustrating the general principles of the present invention and is not meant to limit the inventive concepts claimed herein.

Referring now to FIG. **3**, there is shown a disk drive **300** embodying the present invention. As shown in FIG. **3**, at least one rotatable magnetic disk **312** is supported on a spindle **314** and rotated by a disk drive motor **318**. The magnetic recording on each disk is in the form of an annular pattern of concentric data tracks (not shown) on the disk **312**.

At least one slider **313** is positioned near the disk **312**, each slider **313** supporting one or more magnetic read/write heads **321**. As the disks rotate, slider **313** is moved radially in and out over disk surface **322** so that heads **321** may access different tracks of the disk where desired data are recorded. Each slider **313** is attached to an actuator arm **319** by means of a suspension **315**. The suspension **315** provides a slight spring force which biases slider **313** against the disk surface **322**. Each actuator arm **319** is attached to an actuator means **327**. The actuator means **327** as shown in FIG. **3** may be a voice coil motor (VCM). The VCM comprises a coil movable within a fixed magnetic field, the direction and speed of the coil movements being controlled by the motor current signals supplied by controller **329**.

During operation of the disk storage system, the rotation of disk **312** generates an air bearing between slider **313** and disk surface **322** which exerts an upward force or lift

on the slider. The air bearing thus counter-balances the slight spring force of suspension **315** and supports slider **313** off and slightly above the disk surface by a small, substantially constant spacing during normal operation.

The various components of the disk storage system are controlled in operation by control signals generated by control unit **329**, such as access control signals and internal clock signals. Typically, control unit **329** comprises logic control circuits, storage means and a microprocessor. The control unit **329** generates control signals to control various system operations such as drive motor control signals on line **323** and head position and seek control signals on line **328**. The control signals on line **328** provide the desired current profiles to optimally move and position slider **313** to the desired data track on disk **312**. Read and write signals are communicated to and from read/write heads **321** by way of recording channel **325**.

The above description of a typical magnetic disk storage system, and the accompanying illustration of FIG. **3** are for representation purposes only. It should be apparent that disk storage systems may contain a large number of disks and actuators, and each actuator may support a number of sliders.

FIG. **4** is a side cross-sectional elevation view of a merged magnetic head **400**, which includes a write head portion **402** and a read head portion **404**, the read head portion employing a dual spin valve sensor **406** of the present invention. FIG. **5** is an ABS view of FIG. **4**. The spin valve sensor **406** is sandwiched between nonmagnetic electrically insulative first and second read gap layers **408** and **410**, and the read gap layers are sandwiched between ferromagnetic first and second shield layers **412** and **414**. In response to external magnetic fields, the resistance of the spin valve sensor **406**

changes. A sense current (I_s) conducted through the sensor causes these resistance changes to be manifested as potential changes. These potential changes are then processed as readback signals by the processing circuitry **329** shown in FIG. **3**.

The write head portion **402** of the magnetic head **400** includes a coil layer **422** sandwiched between first and second insulation layers **416** and **418**. A third insulation layer **420** may be employed for planarizing the head to eliminate ripples in the second insulation layer caused by the coil layer **422**. The first, second and third insulation layers are referred to in the art as an "insulation stack". The coil layer **422** and the first, second and third insulation layers **416, 418** and **420** are sandwiched between first and second pole piece layers **424** and **426**. The first and second pole piece layers **424** and **426** are magnetically coupled at a back gap **428** and have first and second pole tips **430** and **432** which are separated by a write gap layer **434** at the ABS. Since the second shield layer **414** and the first pole piece layer **424** are a common layer this head is known as a merged head. In a piggyback head an insulation layer is located between a second shield layer and a first pole piece layer. First and second solder connections (not shown) connect leads (not shown) from the spin valve sensor **406** to leads (not shown) on the slider **313** (FIG. **3**), and third and fourth solder connections (not shown) connect leads (not shown) from the coil **422** to leads (not shown) on the suspension.

FIG. **6** is an enlarged isometric ABS illustration of the read head **400** shown in FIG. **4**. The read head **400** includes the spin valve sensor **406**. First and second hard bias and lead layers **602** and **604** are connected to first and second side edges **606** and **608** of the spin valve sensor. This connection is known in the art as a contiguous junction and is fully described in U.S. Pat. 5,018,037 which is incorporated by reference herein. The first

hard bias and lead layers **602** include a first hard bias layer **610** and a first lead layer **612** and the second hard bias and lead layers **604** include a second hard bias layer **614** and a second lead layer **616**. The hard bias layers **610** and **614** cause magnetic fields to extend longitudinally through the spin valve sensor **406** for stabilizing the magnetic domains therein. The spin valve sensor **406** and the first and second hard bias and lead layers **602** and **604** are located between the nonmagnetic electrically insulative first and second read gap layers **408** and **410**. The first and second read gap layers **408** and **410** are, in turn, located between the ferromagnetic first and second shield layers **412** and **414**.

The present invention provides a new sensor structure in which particular layers of a free layer structure are pinned antiparallel to each other and extend beyond the track width of the sensor. A third layer is added to the free layer structure in the track width to increase the net magnetic thickness of the free layer structure. This novel structure has been found to increase both the stability of the free layer structure and improve track definition by reducing the effect of magnetic influences of side tracks. Many types of heads can use the structure described herein, and the structure is particularly adapted to CPP GMR sensors and CPP tunnel valve sensors. In the following description, the track edges of the layers are defined by the track width (W). The sensor height is in a direction into the face of the paper in an ABS view. Unless otherwise described, thicknesses of the individual layers are taken perpendicular to the plane of the associated layer and are provided by way of example only and may be larger and/or smaller than those listed. Similarly, the materials listed herein are provided by way of example only, and one skilled in the art will understand that other materials may be used without straying from

the spirit and scope of the present invention. Also, the processes used to form the structures are conventional.

CPP GMR

FIG. **7** depicts an ABS view of a CPP GMR sensor **700** according to one embodiment. "CPP" means that the sensing current ($\mathbf{I_s}$) flows from one shield to the other shield in a direction perpendicular to the plane of the layers forming the sensor **700**.

As shown in FIG. **7**, a first shield layer (S1) **702** is formed on a substrate (not shown). The first shield layer **702** can be of any suitable material, such as permalloy (NiFe). An illustrative thickness of the first shield layer is in the range of about 0.5 to about 2 μm.

Seed layers are formed on the first shield layer **702**. The seed layers aid in creating the proper growth structure of the layers above them. Illustrative materials formed in a stack from the first shield layer **702** are a layer (SL1) **704** of Ta, a layer (SL2) **706** of NiFeCr, and a layer (SL3) **708** of either Ru or Cu. Illustrative thicknesses of these materials are Ta (30Å), NiFeCr (40Å), and Ru or Cu (10Å). Note that the stack of seed layers can be varied, and layers may be added or omitted based on the desired processing parameters.

Then a free layer structure **710** is formed above the seed layers. The magnetic orientation of the free layer structure **710** must be preset during manufacture, otherwise the orientation will be unstable and could move around at random, resulting in a "scrambled" or noisy signal. This instability is a fundamental property of magnetically soft materials, making them susceptible to any external magnetic perturbations. Thus, the

magnetic orientation of the active area of the free layer structure **710** should be stabilized so that when its magnetic orientation moves, it consistently moves around in a systematical manner rather than a random manner. The magnetic orientation of the active portion of the free layer structure **710** should also be stabilized so that it is less susceptible to reorientation, i.e., reversing. The structure disclosed stabilizes the free layer structure **710**.

As shown, the free layer structure **710** has first, second, and third magnetic layers (FL1), (FL2), (FL3) **712, 714, 718**, respectively. The first and second layers **712, 714** extend beyond the track width **W** and are separated by a thin layer of antiparallel coupling material (APC1) **716**. The antiparallel coupling layer **716** causes the magnetic orientations of the first and second layers **712, 714** in the free layer structure **710** to be oriented antiparallel to each other. The third layer **718** is about as wide as the track width **W**. In the central portion defined by the track width **W**, the second and third layers **714, 718** are ferromagnetically exchange coupled parallel to each other. The resulting free layer structure **710** can be called a synthetic antiparallel coupled free layer structure.

Preferably the first and second layers **712, 714** have about the same magnetic thickness. In the end regions, defined as outside the track width **W**, the magnetic orientations of the first and second layers **712, 714** are strongly pinned and are therefore unaffected by external magnetic forces, such as those created by adjacent tracks on a magnetic media passing thereby. However, the net magnetic thickness of the second and third layers **714, 718** in the central portion (in the track width **W**) is larger than the thickness of the first layer **712**. The larger net magnetic moment of the second and third layers **714, 718** allows the free layer structure **710** to create signal variations when acted

upon by external magnetic forces such as those created by magnetic media passing thereby.

For manufacturing ease, the first and second layers can be made very wide relative to the track width **W**, which is currently less than about 0.1 μm. As a minimum, the portions of the first and second layers **712, 714** outside the track edges are each at least about as wide as the track width **W**. Preferably, the total length of first and second layers is about five times the track width **W** or more.

Because the net thickness of the second and third layers **714, 718** can be adjusted by varying the thickness of the third layer **718**, the free layer structure **710** so can be designed to any desired magnetic thickness. For example, suppose a free layer magnetic thickness of 30Å is desired, and the first and second layers **712, 714** are each 15Å thick. Because the first and second layers **712, 714** have about the same magnetic thickness and are AP coupled, the third layer thickness is formed to 30Å. Thus, the thickness of the first layer **712** is 15Å, and the total thickness of the second and third layers **714, 718** is 45Å, and the net magnetic thickness of the free layer structure **710** is 30Å.

Because the pinning strength of the first and second layers **712, 714** becomes weaker as the width of the layers is decreased, the magnetic orientations of the first and second layers **712, 714** tend to become unpinned under electrical/mechanical stress. To overcome this tendency to flip, the first and second layers **712, 714** are made wider than the track width **W**. This is permissible because the first and second layers **712, 714** do not affect the effective track width **W** of the sensor **700**.

As the portions of the first and second layers **712, 714** in the track width **W** try to flip under electrical/mechanical stress, the areas of the first and second layers **712, 714**

outside the track edges of the sensor prevents the magnetic orientations of the first and second layers **712, 714** from flipping. Because the first and second layers **712, 714** are longer, the first and second layers **712, 714** have higher magnetic stability from the shape anisotropy. The width **W** of the sensor is very long compared to its height (into the page), this provides larger magnetic anisotropy for stability. The second layer **714** in turn stabilizes the third layer **718** via the ferromagnetic exchange coupling.

Illustrative materials for the first, second and third layers **712, 714, 718** are NiFe, $CoFe_{10}$ (90% Co, 10% Fe), $CoFe_{50}$ (50% Co, 50% Fe), etc. Illustrative thicknesses of the first and second layers **712, 714** are between about 10Å and 30Å. An illustrative thickness of the third layer **718** is between about 10 and 50Å. The Ru layer **716** can be about 5-15Å, but is preferably selected to provide a saturation field above about 10 KOe. In a preferred embodiment, each of the pinned first and second layers **712, 714** is about 15Å with an Ru layer **716** therebetween of about 8Å.

Several benefits of the synthetic free layer structure **710** described herein are achieved over known sensor structures. Because the outside portions of the first and second layers **712, 714** have near identical magnetic thicknesses, they do not generate any signal. Thus, track definition is better because, as the outside portions of the first and second layers **712, 714** do not generate any signal, side reading is reduced or eliminated. The pinning of the first and second layers **712, 714** also stabilizes the free layer such that no in-stack bias layer or peripheral hard bias layer is necessary. Further, the total magnetic thickness of the free layer structure **710** can be made much larger. In addition, the free layer structure **710** is much more magnetically stable at high temperatures.

In addition to the improvement provided by the longer pinned first and second layers **712, 714**, outer portions of first and second layers **712, 714** can be pinned by an antiferromagnetic layer (AFM) **719**. The pinning by the AFM layer **719** creates interlayer exchange coupling that carries over to the portions of the first and second layers **712, 714** positioned within the track width. In particular, the first and second layers **712, 714** are exchange coupled with each other, the portions of the pinned layers first and second layers **712, 714** inside the track width are exchange coupled with the portions of the first and second layers **712, 714** outside the track width, and the portions of the first and second layers **712, 714** outside the track width are exchange coupled with the AFM layer **719**. Thus, the effects of the AFM layer **719** travel throughout the first and second layers **712, 714**. The zero net moment of the free layer structure **710** coupled with the additional pinning by the AFM layer **719** assures strong pinning. In fact, the first and second layers **712, 714** are pinned so strongly that virtually no external magnetic or electrical force will be able to disrupt the magnetic orientations of the first and second layers **712, 714**.

The AFM layer **719** is spaced apart from the portions of the sensor **700** within the track width because otherwise the AFM layer **719** would shunt current. Preferably, the space between the AFM layer **719** and the track edges of the sensor is about 0.1 micron or more. The gap can be smaller, but it will reduce free layer sensitivity. The effects of the AFM layer **719** are enhanced because the AFM layer **719** is positioned outside the track width, and therefore stays cooler because no current flows though it. This design provides a further advantage in that because the AFM layer **719** is not positioned in the sensor stack, thus reducing the gap of the sensor. Preferred materials for the AFM layer

719 are PtMn, IrMn, etc. The thickness of the AFM layer **719** can be about 60-150 Å if it is constructed from PtMn, and about 30-80 Å if it is constructed from IrMn, regardless of the thicknesses of the first and second layers **712, 714**. The thickness of the AFM layer **719** is may be varied because the net moment of the pinned layer structure **710** is about zero.

A first spacer layer (SP1) **720** is formed above the free layer structure **710**. Illustrative materials for the first spacer layer **720** include Cu, CuO_x, Cu/$CoFeO_x$/Cu stack, etc. The first spacer layer **720** can be about 10-40Å thick, preferably about 30Å.

Then an antiparallel (AP) pinned layer structure **721** is formed above the first spacer layer **720**. As shown in FIG. **7**, first and second AP pinned magnetic layers, (AP1) and (AP2) **722, 726**, are separated by a thin layer of an antiparallel coupling material (APC2) **724** such that the magnetic moments of the AP pinned layers **722, 726** are self-pinned antiparallel to each other. The pinned layers **722, 726** have a property known as magnetostriction. The magnetostriction of the pinned layers **722, 726** is very positive. The sensor **700** is also under compressive stresses because of its geometry at the ABS, and the configuration of the layer is such that it produces very large compressive stress. The combination of high positive magnetostriction and compressive stress causes the pinned layers **722, 726** to develop a magnetic anisotropy that is in a perpendicular direction to the track width. This magnetic coupling through the Ru spacer causes the pinned layers **722, 726** to have antiparallel-oriented magnetizations.

In the embodiment shown in FIG. **7**, the preferred magnetic orientation of the pinned layers **722, 726** is for the first pinned layer **722**, into the face of the structure depicted (perpendicular to the ABS of the sensor **700**), and out of the face for the second

pinned layer **726**. Illustrative materials for the pinned layers **722, 726** are $CoFe_{10}$ (90% Co, 10% Fe), $CoFe_{50}$ (50% Co, 50% Fe), etc. separated by a Ru layer **724**. Illustrative thicknesses of the first and second pinned layers **722, 726** are between about 10Å and 25Å. The Ru layer **724** can be about 5-15Å, but is preferably selected to provide a saturation fields above about 10 KOe. In a preferred embodiment, each of the pinned layers **722, 726** is about 18Å with an Ru layer **724** therebetween of about 8Å.

A cap (CAP) **728** is formed above the bias layer **726**. Exemplary materials for the cap **728** are Ta, Ta/Ru stack, etc. An illustrative thickness of the cap **728** is 20-30Å.

A second shield layer (S2) **730** is formed above the cap **728**. An insulative material **732** such as Al_2O_3 is formed on both sides of the sensor stack.

FIG. **8** depicts an ABS view of a CPP GMR sensor **800** according to another embodiment. The CPP GMR sensor **800** generally has the same configuration as the structure shown in FIG. **7**, except that the AFM layer **719** has been removed. The end regions of the first and second layers **712, 714** will not generate any signal if the magnetic thicknesses of the first and second layers **712, 714** are substantially matched, as the end regions are self-pinned.

However, the AFM layer **719** enhances the pinning of the end regions of the first and second layers **712, 714**, and thus the magnetic stability of the first and second layers **712, 714**, and so is preferred.

FIG. **9** depicts an ABS view of a CPP GMR sensor **900** according to another embodiment. The CPP GMR sensor **900** generally has the same configuration as the structure shown in FIG. **7**, except that the second shield layer **730** extends downwardly so that it is positioned along a portion of the sensor stack. This design provides better track

resolution, because the second shield layer **730** is closer to the free layer structure **710**. Magnetic fields from adjacent tracks are drawn to the second shield layer **730**, and therefore do not interfere with the reading function.

CPP Tunnel Valve

FIG. **10** depicts an ABS view of a CPP tunnel valve sensor **1000** according to one embodiment. The CPP tunnel valve sensor **1000** generally has the same configuration as the structure shown in FIG. **7**, except that the first spacer layer **720** is formed of a dielectric barrier material, such as, Al_2O_3, AlO_x, MgO_x, etc. The first spacer layer **720** is very thin such that the electric current passing through the sensor **1000** "tunnels" through the first spacer layer **720**. An illustrative thickness of the first spacer layer **720** is 3-6Å.

CIP GMR

The concepts described above can also be adapted to create a CIP GMR sensor, as will be apparent to those skilled in the art. "CIP" means that the sensing current (**I_s**) flows from in a direction parallel to or "in" the plane of the layers forming the sensor. The CIP GMR sensor generally has the same configuration as the structures shown in FIGS. **7-10**, except that leads of conventional materials and thicknesses are formed on opposite sides of the sensor and the sensor is sandwiched between an insulative material rather than shields.

In one method to fabricate the sensors shown in FIGS. **7-10**, the layers **702-728** (except the AFM layer **719**) are formed. A resist mask is formed on the cap layer **728** to cover and define the track width W. The structure is etched or milled down to second

layer **714**. If an AFM layer **719**, is to be added, it is formed on the second layer **714**. The structure areas outside the track edges are then filled with Al_2O_3 **732**. The structure is planarized via chemical-mechanical polishing (CMP). Then the second shield layer **730** is formed.

Another method to fabricate the sensors shown in FIGS. **7-10** is to form layers **702-714**. A resist mask is formed outside the desired track edges, leaving the track width **W** exposed. The remaining layers **718-728** are formed in the track width **W** defined between the mask edges. The resist is removed. If an AFM layer **719**, is to be added, it is formed on the second layer **714**. The structure areas outside the track edges are then filled with Al_2O_3 **732**. The structure is planarized via chemical-mechanical polishing (CMP). Then the second shield layer **730** is formed.

While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. For example, the structures and methodologies presented herein are generic in their application to all MR heads, AMR heads, GMR heads, TMR heads, CPP GMR heads, etc. Thus, the breadth and scope of a preferred embodiment should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.